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A review of challenges and framework development for corrosion fatigue life assessment of monopile-supported horizontal-axis offshore wind turbines

Victor Okenyi[a], Mahdi Bodaghi[a], Neil Mansfield[a], Shukri Afazov[a] and Petros Siegkas[b]

[a]Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham, UK; [b]Department of Mechanical Engineering and Materials Science and Engineering, Cyprus University of Technology, Limassol, Cyprus

ABSTRACT
Digital tools such as machine learning and the digital twins are emerging in asset management of offshore wind structures to address their structural integrity and cost challenges due to manual inspections and remote sites of offshore wind farms. The corrosive offshore environments and salt-water effects further increase the risk of fatigue failures in offshore wind turbines. This paper presents a review of corrosion fatigue research in horizontal-axis offshore wind turbines (HAOWT) support structures, including the current trends in using digital tools that address the current state of asset integrity monitoring. Based on the conducted review, it has been found that digital twins incorporating finite element analysis, material characterisation and modelling, machine learning using artificial neural networks, data analytics, and internet of things (IoT) using smart sensor technologies, can be enablers for tackling the challenges in corrosion fatigue (CF) assessment of offshore wind turbines in shallow and deep waters.

Abbreviations: ANN, Artificial Neural Network; CF, Corrosion Fatigue; CPFE, Crystal Plasticity Finite Element; DT, Digital Twin; FCGR, Fatigue Crack Growth Rate; FEA, Finite Element Analysis; HAOWT, Horizontal-Axis Offshore Wind Turbine; HAZ, Heat-Affected Zone; IoT, Internet of Things; ML, Machine Learning; O&M, Operation and Maintenance; RS, Residual Stress; SCADA, Supervisory Control and Data Acquisition; SIF, Stress Intensity Factor

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KEYWORDS
Offshore wind turbine; fatigue; corrosion; artificial neural network; condition monitoring; digital twin

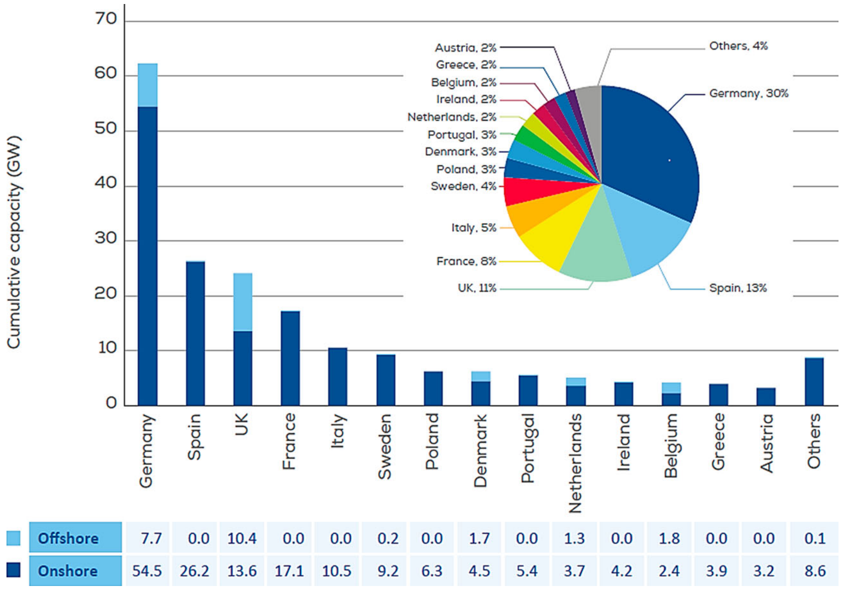
1. Introduction

Offshore wind power is rapidly growing, and the number of offshore wind turbines installed in 2021 tripled those installed in 2020, taking global capacity to 48.2 GW (Lee and Zhao 2021). In 2020, the UK had the highest total offshore wind power capacity of 10.4 GW (see Figure 1; Wood Mackenzie 2020). The UK is one of the lead offshore wind power generation countries with a capacity of 20–55 GW planned to be installed by 2050 (James and Ros 2015). With a need for advancement in durability, more research resources for new materials are being considered in offshore structures (Wood Mackenzie 2020). From design considerations, production, and cost optimisations literature (Muskulus and Schafhirt 2014; Wu et al. 2014; Chehouri et al. 2015; Gentils et al. 2017; Hou et al. 2017), reducing high energy costs requires building offshore wind farms capable of producing more energy. This directly translates into building larger offshore wind turbines that will require larger substructures to support them. Data from offshore wind farms across Europe show that as offshore wind turbine installations move into deeper waters leading to increase in the investment costs due to an increase in operation and maintenance costs (Morthorst and Kitzing 2016). Wind turbines with a capacity to produce over 10 MW were first manufactured in 2018, with foundation costs corresponding to more than 20% of its capital cost (Kim and Kim 2018). With advancements in design and construction, there are now next-generation horizontal-axis offshore wind turbine (HAOWT) prototype of 15 MW capacity set to be built from 2022 using monopile foundations (Vestas 2021).

Challenges facing the wind energy sector include aerodynamic and hydrodynamic effects, soil-structure interaction, design optimisation, environmental factors related to harsh operating conditions, excessive costs associated with manufacturing, installation, building, operation, and maintenance. There are physical asset management challenges due to the remote location of these structures in deeper waters as well as life performance challenges due to higher wind loads and lower fatigue performance at the welds (e.g. welded monopile sections experiencing transient stress fields) (Igwemezie et al. 2018).

Fatigue in HAOWT operation is caused by cyclic mechanical loadings and enhanced by the marine environments where corrosion is a major degradation factor. Thus, corrosion fatigue (CF) is a type of damage to the material under cumulative cyclic loading in a corrosive environment (Suresh 1992). Fatigue damages and rate of crack growth in metallic materials are accelerated by corrosion with a potential cause of fractures, rapid ageing, and failure of engineered systems with pitting being its most detrimental factor. CF of structural members is still a principal concern in the foundations of offshore wind turbines (Dong et al. 2012), where the cost of maintenance against CF could be seen as an important domain because 98% of the support structures are made of structural steel (Ancona and Jim 2001). Pitting is important to the life span of the structure (Melchers 2010), which requires further research to understand its effect on offshore wind turbine monopile structural steel materials. Pitting and CF have been researched in other sectors

CONTACT Mahdi Bodaghi mahdi.bodaghi@ntu.ac.uk Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham NG11 8NS, UK



	Germany	Spain	UK	France	Italy	Sweden	Poland	Denmark	Portugal	Netherlands	Ireland	Belgium	Greece	Austria	Others
Offshore	7.7	0.0	10.4	0.0	0.0	0.2	0.0	1.7	0.0	1.3	0.0	1.8	0.0	0.0	0.1
Onshore	54.5	26.2	13.6	17.1	10.5	9.2	6.3	4.5	5.4	3.7	4.2	2.4	3.9	3.2	8.6

Figure 1. Offshore wind power capacity in 2020 in Europe (Wood Mackenzie 2020). (Image published with kind permission by WindEurope) (This figure is available in colour online).

as well, such as electric power generation (e.g. nuclear), aerospace (e.g. high-pressure turbine blades), marine (e.g. ships and submarines), oil and gas, and construction (e.g. bridges) (Larrosa et al. 2018).

Support structures consist of jackets, gravity foundations, tripods, suction caissons, and monopiles with and without floating substructures (O'Kelly and Arshad 2016). Monopiles are the most common foundation type used in up to ∼96% of running offshore wind turbines in the UK (Higgins and Foley 2014). They are installed in sea depths of approximately 35 m, however, they could also be deployed in deeper waters. Between January and June 2017, about 110 foundations were installed in the UK (Wind Europe 2017) showing an increase in offshore wind turbine growth. A typical large monopile with circumferential weld, fabricated for an offshore wind farm, is shown in Figure 2. The economic consideration of monopiles in HAOWT applications emanates from its effectiveness in reducing material maintenance costs (Oh et al. 2013). The currently installed monopiles are becoming larger in diameter and height, and a direct relationship between wind speed and tower height has been established for improved power generation (Lavanya and Kumar 2020). A further 15% tower height increase is predicted between 2020 and 2025 leading to a tower height of about 150 m (Igwemezie et al. 2019). Recently, research has been conducted to explore the incorporation of high strength concrete in producing hybrid monopiles (Jammes et al. 2013; Chen et al. 2018; Ma and Yang 2020).

Understanding the mechanical response of support structures, especially monopiles with large diameters presently used in HAOWT, requires closer research attention due to their recent developments and exploitation. The loads and larger bending moments could be a source of concern in deeper waters. Several experiments and modelling techniques have been applied over the years to study the CF by using damage theories (Rejovitzky and Altus 2013; Adedipe et al. 2015; Bergara et al. 2017; Sun

Figure 2. A fabricated monopile for an offshore wind farm (Kallehave et al. 2015) (This figure is available in colour online).

and Jahangiri 2019). Further studies on the mechanics of support structures would be required to understand the fatigue mechanisms in the support structures in aggressive environments.

Recent technological advancements in computational simulation tools, the internet of things (IoT), real-time monitoring, and material performance evaluation of HAOWT have shown promising results in effective physical asset management by collecting and analysing data from multiple structures. Digital twins (DT) can be employed to reproduce real-world scenarios in a digital replica with embedded sensors to automate, optimise, diagnose, maintain, and repair assets (i.e. HAOWT). This is especially useful in deeper waters, where manual inspection could be expensive, inefficient, and associated with high risks (Wang 2020). DT technologies have the potential to enable engineers to gain more operational information and allow them to make better decisions to extend the lifespan of large HAOWT. Research on fatigue degradation under corrosion of existing and newer steel grade materials incorporating the use of digital tools and operational data is still not fully explored. The behaviour of steel materials for monopile support structures in marine environments under the influence of mechanical and environmental factors especially more advanced S355 thermomechanical rolled steel requires further research to understand how the fatigue properties change as the size of HAOWTs materials tend to enlarge since size effects have been observed (Ólafsson et al. 2016). Also, holistic modelling tools for on-line monitoring and prognostic maintenance of HAOWT are required to be further developed.

This review is conducted as a number of support structure collapses have taken place over the last two decades where the risk of future collapses is still a concern. Reported cases have shown aerodynamic effects through typhoons and storms to be the most critical factors for wind turbine collapse while environmental damages are also encountered (Ma et al. 2019). These damages were also observed to occur mostly at the initial life stage and the end-of-life stages. Thus, as we consider corrosion which is a form of environmental damage, the cyclic loading effect must be considered as both these factors are key drivers for CF damage. A proposed methodological framework has been applied in this review as illustrated in Figure 3. The three main stages of the methods include: a wide-range review to identify challenges faced in practice; collection of facts to make observation on progress and identify possible solutions; and proposal of a framework incorporating digital tools to address these challenges. Across this review, trends from over 130 publications have been considered as well as industry reports to provide means of better assessing CF to ensure serviceable life, especially in HAOWT supported by monopiles.

This study aims to provide a review of the challenges in fatigue of HAOWT monopile supported structures with the view to address the digital challenges as well as design and physical challenges as illustrated in Figure 4. This review is not meant to be exhaustive, but it would offer the most prominent advances to encourage further prospective studies.

2. Understanding fatigue and corrosion in offshore structures

The synergy between corrosion and fatigue produces a detrimental effect on a metallic material. CF is an environmental time-dependent electrochemical process occurring at the slip steps or the crack tip with two major mechanisms of anodic slip dissolution and hydrogen embrittlement. Reduced crack growth rates could also occur as corrosion products may cause an oxide-induced crack closure effect owing to elasticity around the crack tip which prevents plastic deformation or a decrease in stress intensity factor (SIF) as crack width grows (Pippan and Hohenwarter 2017; Wu et al. 2020). Thus, loading conditions of frequency and stress waveform occurring in service can affect crack growth caused by anodic dissolution, while protective film rupture rate, passivation rate and solution renewal rate affect hydrogen embrittlement (Suresh 1992).

An increase in pitting resistance suggests a corresponding increase in corrosion-fatigue strength, and a reduction in the failure at the slip zone (Jaske et al. 1981). Pitting corrosion varies depending on different marine zones (Mathiesen et al. 2016). Monopile appears to have a high pitting corrosion rate, and potentially becomes a stress concentrations area for the initiation of fatigue cracks owing to lines of geometric discontinuities in weldments. CF with considered pitting has the following stages (Akid and Richardson 2010; Fatoba 2015): (i) passive film breakdown; (ii) pit initiation; (iii) pit growth; (iv) pit-to-crack transition; (v) short crack growth and long crack growth.

Corrosion ordinarily is affected by chemical, physical, and biological factors (e.g. biofouling, plant, and animal life). However, other factors affect corrosion in aqueous environments which further points out the complex nature of the interaction between corrosion and fatigue and how the former helps the latter. Factors influencing CF have long been categorised into mechanical, metallurgical, and environmental (Wei and Speidel 1972). Some mechanical factors include peak stress (Zhao et al. 2017), cyclic frequency, stress ratio, load waveform (Adedipe et al. 2016; Igwemezie and Mehmanparast 2020), residual stress (RS) (Xin and Veljkovic 2020); metallurgical factors like alloy composition, microstructure (Nicolas et al. 2019), wielding defects, heat treatment (Mehmanparast et al. 2017); environmental factors like pH (Kolawole et al. 2019), temperature (Atkinson and Chen 1993), electrochemical potential (Kovalov et al. 2018), inhibitors (Lindley and Rudd 2001). Material and environmental factors including temperature and pH seem to have a direct impact on pitting CF. As pitting induces localised stress concentrations, they become sites for crack nucleation.

2.1. Loading and operational factors affecting corrosion fatigue process

CF processes in HAOWTs are affected by extreme wave conditions at different exposure levels, operational conditions, and different load combinations. The HAOWT support structures are designed to endure extreme loading events that may occur during operation, such as extreme wind gusts and wave conditions. Extreme wave loading events that occur once every 50 years are frequently considered in design (Arany et al. 2017). Extreme wave loads cause cyclic loading with high velocity and acceleration components, which causes fatigue in the monopile region. These effects, when combined with the several corrosion zones described in DNVGL-RP-0416 (DNV 2016) (see Figure 5), where the rates of material loss per year at various exposure levels are anticipated, can result in devastating CF effects, particularly in the splash zone.

The two principal fatigue load scenarios of regular operation and parked conditions both have high cyclic loads (BSI 2019). For instance, the bending moments (see Figure 5) vary cyclically due to operational rotation of the blades, wind forces on the tower, and wave forces. Other load situations that affect the HAOWT structures are torsional forces, operational centrifugal forces, coriolis forces, and gyroscopic forces (Igwemezie et al. 2019). Thrust force on the rotor has frequently contributed the most effect on HAOWT monopile supported structures (O'Kelly and Arshad 2016; Gentils et al. 2017). Design guidance for loading

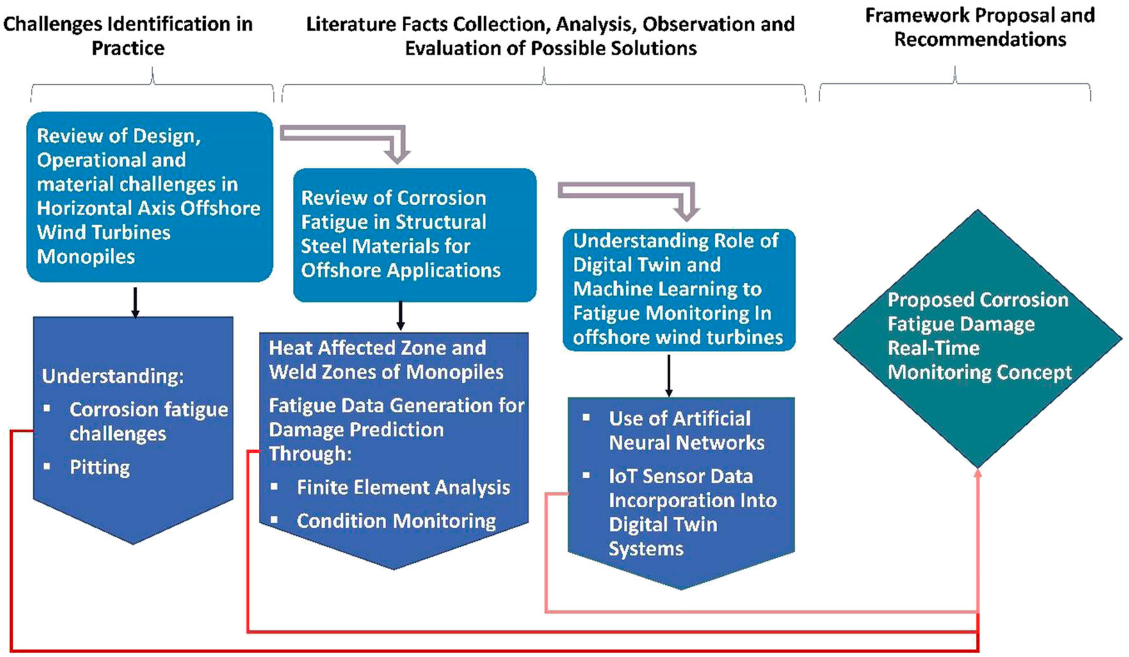


Figure 3. Research review methodology applied in this study (This figure is available in colour online).

combinations for regular and extreme wind and wave situations has been recommended (DNV 2014). This enables the structural performance of offshore wind turbines to be assessed under the most extreme situations. In reality, loading conditions are complex with stochastic nature as they vary with time (DNV and Risø 2002). These factors suggest that for effective assessment of CF in monopile supported HAOWT, corrosion zones, loading sequence and the operational states jointly impact the service life. Additionally, soil-structure interaction which includes the natural frequency of the structure must also be considered in design.

During the concept design stage of a HAOWT, the site of installation must be considered as this factor will influence the wind and wave forces necessary to generate the required power production capacity of the wind turbine. In the initial stages of design, efforts must be paid to the sizing of components such as monopile diameter, blade dimensions, wall thickness, embedded length etc., to ensure structural stability after which loading conditions (ultimate limit states, serviceability states, and fatigue limit states) will be estimated. The final stages must consider design checks for safety, natural frequency, deflection, corrosion and fatigue life estimation to assess the long term performance of the structure.

2.2. Fatigue analysis methods and fracture mechanics model

In understanding CF in engineering structures, there is a need to fully describe the combined effect of mechanical factors and various aggressive environments. Quantifying the effects of aggressive environments in complex synergistic interactions is challenging. Fatigue analysis methods include stress life, strain life, and linear

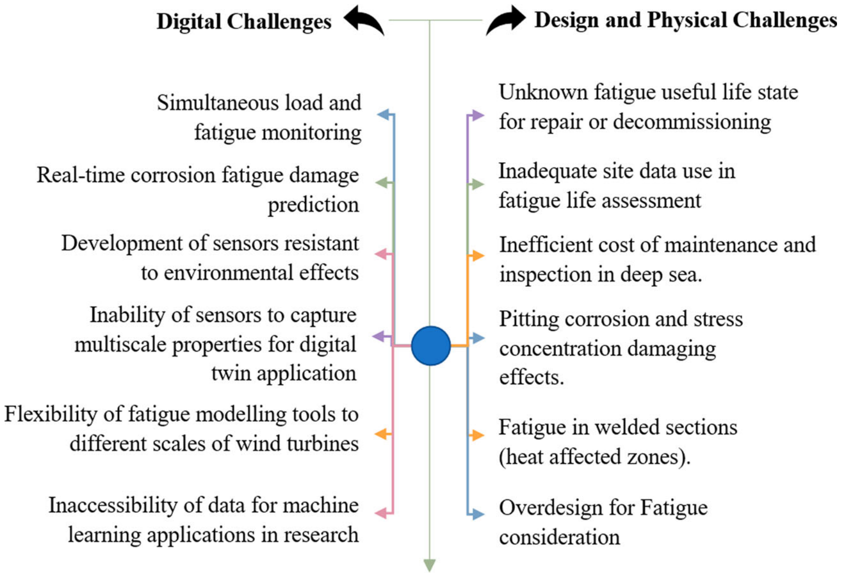


Figure 4. Summary of current fatigue challenges in offshore wind turbine (This figure is available in colour online).

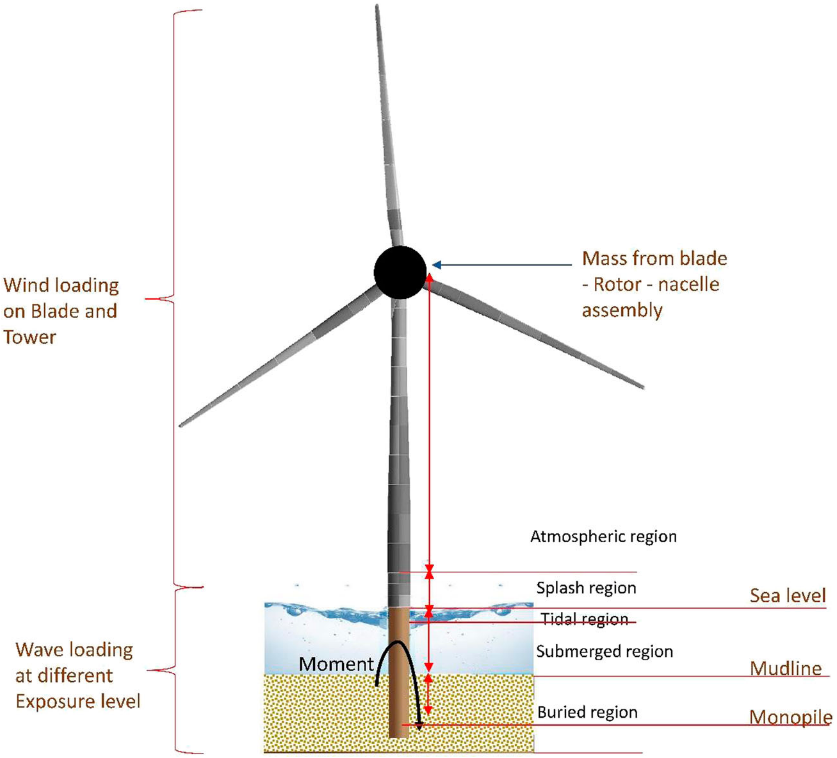


Figure 5. Loads on monopile supported wind turbine at different exposure levels (This figure is available in colour online).

elastic fracture mechanics. Total life (stress and strain life method) or damage tolerance approaches (linear elastic fracture mechanics) are important for the total life assessment to ensure structural integrity and the remaining life of structural materials. The stress life method provides a great quantitative estimation of damage but variations from effects of surface finish, thickness factors and flaw sizes can create inconsistencies (Fatoba 2015). This can affect the accurate estimation of crack initiation. Regardless, the total life method is capable of estimating the life in air or corrosive environments. Table 1 provides a summary of fracture mechanics models for various stages and damage predictions.

From the models presented in Table 1, it is observed that crack growth studies are needed once a crack is initiated. These models will be able to inform the growth of the crack over time and support the estimation of potential risks of ultimate collapse. The usefulness of these models is that they could predict the time between crack initiation and risk of failure based on assumed loads. The presented models in Table 1 show that they have the capability to predict the effects of the environment on fatigue crack propagation using fracture mechanics approaches. Pitting CF in the monopile of the HAOWT structure is important because it is critical to crack nucleation, growth, and the total life of the structure (Larrosa et al. 2018). However, fracture mechanics models are still integrating the holistic impact of mechanical, metallurgical, and environmental factors in pitting CF.

The accumulative fatigue damage approach and the fracture mechanics approach are two different methods that have been applied to fatigue damage assessment for different loading in offshore wind turbine materials. Fatigue life curves represent stress versus number of cycles (S-N curves) while FCGR is depicted by crack length versus number of cycles curve. The fracture mechanics approach and the total life approach have two different philosophies. The fracture mechanics approach based on Table 1 proves to be a more accurate method when applied to corrosion fatigue.

Based on the review of life assessment methodologies, the total life method can be improved by generating S-N curves that have factored in the effect of thickness loss, notch effects, stress concentrations and surface effects in the analyses. The conditions of the remaining surfaces, notches from manufacturing, and installation are factors that will eventually affect the rate of CF damage, and they must be also considered. An example of corrosion protection is the Siemens Gamesa 8 MW HAOWT monopile where the welds are coated to reduce the impact of corrosion on the life.

For damage tolerant methods, crack growth and propagation from corrosion pits can be applied more as a fracture mechanics model at the operation stage and wear-out stage for monitoring damage progression in service. A Vestas V80 2 MW HAOWT reportedly failed due to welding defects (Ma et al. 2019). To consider crack initiation, the heat-affected zones (HAZ) at material weldments should be taken into consideration. While the total life approach which is more of a simplified method could help for design stages, the fracture mechanics which is a detailed method is recommended as a more exact approach as this includes physics related to crack initiation and propagation in fatigue life assessment and failure assessment (Shittu et al. 2021).

3. Corrosion fatigue in materials used in HAOWT fabrication

3.1. Corrosion fatigue on the base material, HAZ, and wield zones in HAOWT

Large structural steel plates are welded in both longitudinal and circumferential directions after rolling and bending to produce monopiles (Jacob et al. 2018). The welding process generates a heat-affected zone (HAZ), which is characterised in general by weak fatigue performance. In the integrity assessment of HAOWT structures subject to wind and wave loads, the weld region is the common site

Table 1. Models in corrosion fatigue studies.

Category	Reference to classical models	Model description	Expression and parameters
Pitting Corrosion Fracture Mechanics Models	Hoeppner Model (Hoeppner 1979)	Critical pit depth prediction facilitating crack nucleation.	$K = 1.1\sigma\sqrt{}\pi(a/Q)$ $d = Ct^3$ (K, σ, a, Q, t, d and C are stress intensity factor, applied stress, pit length, function based on crack shape, time taken to reach pit depth, pit depth and constant dependent upon material and environment)
	Lindley Model (Lindley et al. 1982)	Threshold stress intensity factor ΔK_{th} determination of crack initiation from the pit.	$\Delta K_{th} = \frac{\Delta\sigma\sqrt{}(\pi a)[1.13 - 0.07(a/c)\hat{0}.5]}{1 + 1.47(a/c)1.64]\hat{0}.5}$ ΔK_{th}, a and c and $\Delta\sigma$ are threshold stress intensity factor, minor axis of semi-elliptical crack, major axis of semi-elliptical crack and applied stress range respectively.
	Kawai and Kasai Model (Kawai and Kasai 1985)	Critical pit depth measurement from which fatigue crack grows by determining allowable stress intensity threshold	$\Delta K_{all} = \Delta\sigma_{all}\sqrt{}\pi h_{ma}$ (where ΔK_{all}, $\Delta\sigma_{all}$, F and h_{max} are allowable stress intensity threshold, allowable stress range, geometric factor and maximum pit depth respectively.
	Chen Model (Chen et al. 1996)	Crack initiation prediction from fatigue crack growth rate	$\Delta K_{tr} = \frac{1.12Kt\Delta\sigma\sqrt{}\pi Ctr}{\Phi}$ $(\Delta a/\Delta N)_{pit} = (C_p/2\pi)\ \beta^2 c^{-2}$ $(\Delta a/\Delta N)_{crack} = C_F(k_t\Delta\sigma)^n\ \phi^{-n}c^{0.5n}f$ where ΔK_{tr} is SIF for transition, K_t is elastic stress concentration factor, c is half-pit diameter, Δσ is applied stress range, Φ is shape factor determined by the pit diameter, β is pit aspect ratio, f is cyclic frequency, and C_F, C_p and n are constants.
	Kondo Model (Kondo 1989)	Critical pit condition estimation using stress intensity and pit characteristics	$\Delta K_p = 2.24\sigma_a\sqrt{}\pi c\alpha/Q$ $c = C_p t^{1/3} = Cp(N/f)^{1/3}$ where σ_a, Q, c, t, N, and f represent the stress amplitude, pit aspect ratio, shape factor, pit radius, number of fatigue cycles and cyclic frequency respectively.
Corrosion Fatigue Multi-Stage Predictive Model	Multi-stage Model (Lishchuk et al. 2011)	CF prediction from the combination of pitting corrosion fatigue models at pit growth and crack growth stages	$N_{cf} = N_{sf} + N_{pg} + N_{ptc} + N_{cfsc} + N_{cflc}$ where N_{cf} is the corrosion fatigue life, N_{sf}, number of cycles to scale break down, N_{pg}, the number of cycles for pit growth, N_{ptc}, the number of cycles to pit-to-crack transition, N_{cfsc}, the number of cycles for corrosion fatigue short crack growth and N_{cflc} is the number of cycles to corrosion fatigue long crack growth.
Corrosion Fatigue Predictive Models	Superposition Model (Wei and Gao 1983)	Crack growth rate prediction from the superposition of rate of plasticity-informed crack and a plasticity-chemically-informed crack	$(\Delta a/\Delta N)_e = (\Delta a/\Delta N)_m + (\Delta a/\Delta N)_{cf}$ where $(\Delta a/\Delta N)_e$ is the crack growth rate in an aggressive environment, $(\Delta a/\Delta N)_m$ is the rate of plasticity-driven fatigue crack propagation in an inert environment and $(\Delta a/\Delta N)_{cf}$ is the difference between the total growth rate and 'pure' fatigue growth rate
	The Competition Model (Austen, IM and Walker 1984)	CF crack prediction expressed as competition between mechanical fatigue and CF (when crack growth rate exceeds pit growth rate)	$(\Delta a/\Delta N)_e = (\Delta a/\Delta N)_m\,(\theta) + (\Delta a/\Delta N)_{cf}\,(\theta)$ where $\theta = 1$
	Short Crack Growth Model (Akid and Miller 1991)	Crack growth rate prediction from the addition of crack growth rate in air and crack growth rate in a dissolved environment based on anodic dissolution	$(\Delta a/\Delta N)_{env} = (\Delta a/\Delta N)_{\mathrm{air}} + (\Delta a/\Delta N)_{\mathrm{diss}}$ $(\Delta a/\Delta N)_{\mathrm{diss}} = (Mi_a/ZF\rho)\cdot 1/w$ where M is the atomic weight of the corroding metal, i_a is the anodic dissolution current, Z is the valency, F is the Faraday's constant, ρ is density and w is the cyclic frequency

for fatigue crack nucleation and growth (Mehmanparast et al. 2017). The fatigue resistance in the HAZ is lower than the base material (Kang et al. 2013) indicating a higher possibility of failure in the HAZ. Also, it is worth noting that the initiation and spread of cracks into the base material from HAZ is often in the direction of pipe thickness (Thompson 1984; Healy et al. 1990; Trudel et al. 2014; Mehmanparast et al. 2017). In the recent work by Jacob and Mehmanparast (2021), along the through-thickness, higher fatigue crack growth rate (FCGR) occurred in specimens from the inner surface to the outer surface compared to the vice-versa in seawater (Jacob and Mehmanparast 2021). The residual stresses (RSs) in the HAZ are typically tensile, which contributes to the mean stress effect (Adedipe et al. 2015), especially when a crack starts to grow in welds (Tsay et al. 1999; Mehmanparast et al. 2016; Xin and Veljkovic 2020; Xu et al. 2021). Thus, methods such as post-weld heat treatment can reduce the tensile RS in offshore wind turbines monopile fabrication, hence their life.

The growth of fatigue cracks has been shown under cyclic loading to be greater at the HAZ compared to the base material tested in air under no corrosion (Adedipe et al. 2017). Few research studies were conducted on fatigue crack initiation caused by microstructural defects (Smaili et al. 2019a, 2019b) and the conclusions drawn from these studies showed that weld zones and HAZ must be considered carefully in assessing fatigue crack initiation. The effect of pits on the fatigue performance in the HAZ is a research field that requires more extensive research as environmental conditions grow in harshness.

3.2. Corrosion fatigue in structural steel for HAOWT monopile applications

Structural steel S355 is widely used in the fabrication of most offshore wind monopile due to its weldability characteristics (Healy and Billingham 1998). Materials can be selected according to the recommendations of Det Norske Veritas (DNV 2009). However, as sizes of HAOWT increase, high yield strength structural steels at low temperatures as observed in offshore conditions have been sought to improve their fatigue and corrosion performance. Table 2 shows the mechanical properties of thermo-mechanically rolled weldable fine grain structural steel grades denoted by *M/*

Table 2. Mechanical properties of steel grades in offshore applications according to EN10225 (Oakley Steel 2021).

Mechanical properties Hot rolled plate	EN10225 S355 TMCP Steels			
	S355G8 + M	S355G10 + M	S420G2 + M	S460G2 + M
Yield, σ_y (MPa)				
< Ø16 mm	355	355	420	460
Ø16 mm – Ø25 mm	355	355	400	440
Ø25 mm – Ø40 mm	345	345	390	420
Ø40 mm – Ø63 mm	335	335	380	415
Ø63 mm – Ø100 mm	325	325	380	406 (63–80)/400 (80–100)
Tensile, σ_{UTS} (MPa)				
< Ø40 mm	470–630	470–630	500–660	~520–700
Ø40 mm < Ø100 mm	470–630	470–630	480–640	~500–675
BH	285	285	–	–
EL %	22	22	19	17
E (GPa)	205	205	–	–
υ	0.29	0.29	–	–
M%	55	55	–	–
Charpy V-notch (J)	50@ −40°C	50@ −40°C	–	–

* Ø – thickness; σ_y – Tensile yield strength; σ_{UTS} – Ultimate tensile strength; *BH* – Brinell hardness; *EL* – Elongation at break; *E* – Modulus of elasticity; *υ* – Poisson's ratio; *M* – Machinability.

ML and produced in a highly deoxidised process. *G* denotes that material was produced in a hot rolled process. S355 structural steel is currently used in modern large offshore wind turbines as recommended in BS EN10225 (European Committee for Standarization 2019). These steel grades are reported to have high performance in toughness and weldability (Igwemezie et al. 2018). However, there seems to be limited information regarding material property degradation due to CF and the effects of the full manufacturing process chain.

Finally, corrosion prevention strategies for offshore wind turbine structures and materials exposed to variable loading conditions and harsh environmental conditions were considered. Corrosion mitigation strategies such as spray metallization, galvanic anodes, and external current have been widely considered (Momber 2011; Price and Figueira 2017; Masi et al. 2019). Also, cathodic protection in the submerged zone, coatings in tidal zones, splash zones, and atmospheric zones have been proposed. Mitigating strategies focusing on the reduction of cyclic loads have been researched. For instance, the application of a three-dimensional pendulum tuned mass damper to the HAOWT support structure reduced vibration frequencies and considerably enhanced fatigue life (Mohammadi et al. 2018; Sun and Jahangiri 2019).

3.3. Finite element analysis of corrosion fatigue in high strength steels in offshore wind turbines

Finite element analysis (FEA) can be utilised to predict the stress field in engineering structures subject to loads, which can be used for CF analyses. FEA has been applied in fatigue studies at various scales including:

- Stress assisted corrosion for pitting evolution studies using cellular automation finite element model (Córdoba-Torres et al. 2001; Saucedo-Mora and Marrow 2014; Fatoba et al. 2018; Cui et al. 2019). The model provided useful information on real-time diagnostics of CF i.e. relate changes of depth, aspect ratio, and morphology of pits with time under influence of stress.
- Information on heterogeneous stress, strain, and plastic states leading to crack nucleation using crystal plasticity finite element model (Lu et al. 2014; Castelluccio and McDowell 2015; Signor et al. 2016; Prithivirajan et al. 2021). This model was also able to give valuable information on shape change, rotation, and geometrical dislocations with application in fatigue crack study. This model is useful in the mesoscopic (inter-grain scale, grain cluster scale) and microscopic scales (grain scale, intra-grain scale).
- Multiscale fatigue modelling for the prediction of pit initiation up to long term fatigue crack growth (Anagnostou et al. 2010; Ye et al. 2017). This model used the combined approach of macroscale (where the global state of stress on the component is measured), and mesoscale level (where critical damage site and boundary conditions are extracted from the larger model).

High strength steel has found frequent use in the construction industry due to its high yield strength and low cost (Xin and Veljkovic 2019). FE studies can be found on most steels application in aerospace, nuclear, and oil and gas industries (Deng 2009; Grbovic and Rasuo 2012; Guo et al. 2012; Topaç et al. 2012; Fatoba 2015). FE models on corrosion fatigue of actual sized HAOWTs are commonly not applied due to their heavy computational demands but with recent advancements in desktop computational power, its combination with programming tools could be of greater value to capture deformation in all components with great speed. Table 3 reviewed some applications of FEA on fatigue and CF of steel materials in offshore applications including monopile support structures.

Limited work is currently available on the application of cyclic loading in pit to crack transition on local models. Presently, there is limited literature on the application of cyclic load to pit to crack transition on structural steel materials for offshore applications. FEA has assisted in fatigue damage studies showing that RS values measured in welds can be equal to the yield stress of the material. Other mechanical factors such as mean stress effect, depicted by stress ratio *R* can be found in FEA work but lacks adequate experimental data for its validation in high strength steels.

Some recommendations for future work in FEA could include the use of a wielding interface that could be used to accurately model material properties and capture the microstructural development in the HAZ. Another consideration is the application of computational fluid dynamics coupled with physics-based corrosion to model the interaction between the monopile and seawater to predict pressure distribution and its contribution to corrosion and pit generation, especially in the submerged zone. Computational fluid dynamics can also be used to predict the loads due to wind and the overall flow behaviour in HAOWT farms. Furthermore, a combination of these models with a soil-pile model based on different soil conditions of different geographic zones could have a better

Table 3. A review of FEA of fatigue in high strength steel for offshore applications.

Reference	Fatigue stage	Steel type	FEA results and validation
Xin et al. (2021)	Fatigue crack growth	S355 and S690 steel grade	Results showed that as load ratio increased, the fatigue life of both specimens reduced at a constantly applied stress range. S690 showed higher fatigue strength compared to S355. The FEM results for crack propagation life correlated well with analytical (integration method) results.
Moghaddam et al. (2019)	Corrosion fatigue crack growth	S355 grade steel plates used for mooring points and weldment were considered.	Pit data from service were well captured in the study using FEA method where crack growth was developed in the pit region A higher crack length was observed in the HAZ than the base material as load ratio increased. Thus, higher load ratios, which is more representative of reality, will need to be considered. There was an inadequate range of experimental data for comparison from FEA.
Yeter et al. (2013)	Fatigue failure	S355 steel grade	Worst load case scenario operational conditions were applied. A local FEA model using shell meshing provided detailed results in the critical hotspot region. No validation was reported in the literature.
Jacob et al. (2018)	Fatigue crack growth	S355 G10 + M steel grade	Results showed that residual stress effects would be critical in fatigue crack initiation. Correlation between experimentally measured and predicted FEM residual stresses was demonstrated and showed a similar trend.
Xin and Veljkovic (2019)	Fatigue crack initiation	S355 and S690 steel grade	FEA results showed the earliest fatigue crack initiation at 61% and 81% of total fatigue life for S355 and S690 respectively, implying a better performance of S690 in fatigue resistance although liable to brittleness. Number of fatigue cycles to crack initiation were predicted using FEA and validated against experimental results which showed good correlation.
Rozumek et al. (2018)	Fatigue crack growth	S355J0 steel grade	FEA fatigue crack path simulation was done and showed an agreement with a crack path observed on a real specimen.
Biswal et al. (2021)	Fatigue crack initiation	S355 steel grade	FEA was used to estimate cumulative fatigue damage based on loads from service using an elastic material model.

representation of the induced stresses near the boundary between the soil and the water.

Pit morphology, especially its aspect ratio and location, can be modelled and analysed using FEA. Overall, the availability of experimental data from fatigue tests on steel in marine environments under mechanical and metallurgical factors such as loading frequency, variable amplitude loading interactions, and applied heat treatment methods is limited. The review in Table 3 showed the need to investigate the application of FEA to fatigue initiation studies on a macroscale level for high strength weldable steels in offshore applications. The consideration of aggressive environmental effects, specifically corrosion, would be a significant integration to FEA models of fatigue degradation stages.

3.4. Application of condition monitoring to HAOWT support structures

Condition monitoring has the potential to improve structural reliability and reduce maintenance costs. A preventive based maintenance approach is critical to condition monitoring to reduce the risk associated with physical inspections and ensure that structures are serviceable over an extended period. Apart from time-based preventive maintenance, there are also corrective maintenance and predictive maintenance which are condition-based. Condition monitoring techniques applied in offshore wind turbines can include vibration analysis, strain monitoring, acoustic emission, thermography, electric signals, and shock pulse method (Dhillon 2002).

Results from a failure mode analysis are presented in Figure 6. The number of failure modes associated with the support structure in offshore wind turbines appears to be the highest. Condition monitoring could be useful in reliability assessment by using data acquisition and signal processing tools for monitoring different components of an offshore wind turbine. A review was conducted for the condition-based maintenance in an offshore wind turbine (Scheu et al. 2019), where it was reported that signals obtained from various measurements required complex analyses to estimate the remaining life of components. It was also reported that a real-time damage calculation would provide more feasible solutions.

Supervisory control and data acquisition (SCADA) system data analysis and wind turbine condition monitoring systems are tools applied in condition monitoring of some offshore wind turbines by offering cost-effective data sensing and collection. SCADA systems can collect operational data (including temperatures, currents, pressures, wind speed, and direction) in real-time. Signals are measured at 10 min intervals with a low sampling frequency of 1 Hz. These systems are of importance to researchers in damage diagnostics and prognostics. Wind turbine condition monitoring systems have a higher sampling frequency and can conduct diagnosis and prognosis. The combination of these systems could be useful in larger HAOWT. Smart monitoring has been suggested and encouraged in automated monitoring systems to help engineers in the detection of deviations from measured data (Tchakoua et al. 2014).

Some works have specifically considered health monitoring tools used on monopiles (Bang et al. 2012; Devriendt et al. 2014; Zhou et al. 2019; Jeong et al. 2020) for static and dynamic analysis in which strain and deflection due to bending were obtained using accelerometers and wireless sensors. Ziegler et al. (2017) applied a stochastic extrapolation algorithm and a single strain monitoring measurement to predict strains in other parts of the structure. Most of these works have been done on actual size HAOWTs. However, faster, and more extensive laboratory testing could also be conducted on scaled-down in size HAOWTs (e.g. to develop and validate a health monitoring technology and fatigue assessment methods). Real-time condition monitoring appears more widely applied to wind turbine components such as the blade, gearbox, nacelle, and drivetrain, but not so much in fatigue damage assessment despite the possibility of potential critical failure. A combination of FEA and fatigue analyses with experimental data from real-time condition monitoring could enable real-time fatigue damage calculations to estimate remaining life.

4. Application of artificial neural network to fatigue applicable to HAOWT structures

Artificial neural network (ANN) is a machine learning (ML) technique and one of the widely used predictive methods based

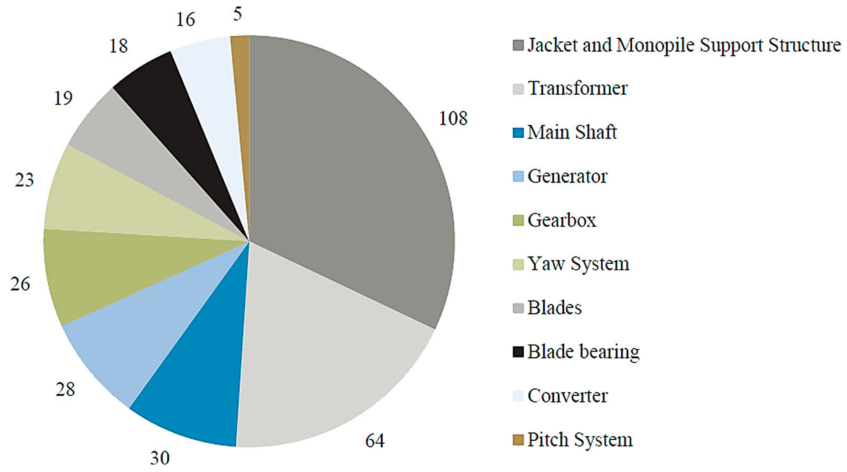


Figure 6. Failure modes in offshore wind turbine main systems (Scheu et al. 2019) (This figure is available in colour online).

on data (Arcos Jiménez et al. 2017). It can be applied either for tracing patterns or approximating data output. It is employed in wind power generation as part of the need to employ tools for reliability, optimised performance, and maintenance using multi-layer networks for non-linear generalisations (Hertz 2018). For instance, feedforward network was used for fatigue life assessment using aerodynamic and hydrodynamic forces as inputs (Tian et al. 2011). The back-propagation network and radial basis function neural network have been also used while the availability of more viable data in recent years has also increased the application of neuro-fuzzy networks (Ata and Kocyigit 2010). Researchers have reported the use of ANN in wind power forecasting (Lin and Liu 2020), HAOWT support structure design optimisation (Stieng and Muskulus 2020; Ziane et al. 2021), and fault detection in HAOWT tower structure (Qiu et al. 2020). Marugán et al. (2018) highlighted that ANN has been used for: 38% for forecasting, 29% for fault detection, 23% for control, and 10% for design. Low cycle fatigue prediction using multi-layer perception and back-propagation ANN was applied to 316L(N) stainless steel (Srinivasan et al. 2003) with core inputs being temperature, strain rate and amplitude. Predicted fatigue life results showed a close match with results from experiments comparing the root mean square values. Most of the ANN time-based predictions have also proved to show better performance over frequency-based prediction, which is fast, but results have shown some conservative fatigue life predictions (Durodola et al. 2017). One challenge of ANNs is their limitations in prediction where extrapolating beyond the available data set is conducted. For example, an ANN predicting fatigue life under low cycle fatigue cannot accurately extrapolate data to predict high cycle fatigue if the data for high cycles is not available. Many studies have applied ANN to fatigue crack growth and CF predictions (Haque and Sudhakar 2001; Gope et al. 2015; Wang et al. 2017; Mortazavi and Ince 2020), where the most used method was the back-propagation network. Similar neural network has been applied in a single layer feed-forward ANN to predict a crack growth (Huang et al. 2006).

One of the many advantages of the application of ANN to HAOWT is their ability to perform fast calculations for on-line monitoring (Marugán et al. 2018). ANN techniques in the literature have majorly been applied to components such as rotors, blades generator, gearbox and bearing while a few have considered tower structures and structural steel materials. Its application could extend to fault diagnostics and forecasting of monopile

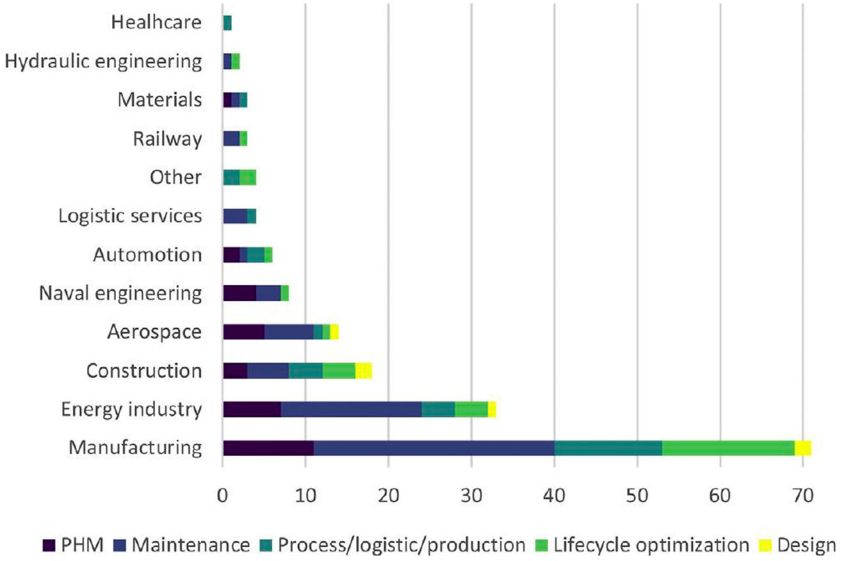


Figure 7. DT maintenance applications to different economic sectors (Errandonea et al. 2020) (This figure is available in colour online).

Table 4. Review of DT applicable to HAOWT.

Reference	DT research conducted	Area of DT application in HAOWT	Key benefits	Observations
Sivalingam et al. (2018)	Studied the application of DT for prediction of remaining fatigue life in a power converter of an HAOWT subjected to thermal cycles.	Damage prediction.	DT monitoring was shown to be more realistic over statistical methods. Main factors affecting the remaining life in components were observed.	The framework could allow for the consideration of boundary conditions present in a specific HAOWT structure.
Johansen and Nejad (2019)	Researched DT condition monitoring for drivetrains in marine applications.	Condition-based monitoring.	DT model-based framework was recommended for fault diagnostics.	A digital twin of a simple drivetrain test rig has been demonstrated utilising different modelling approaches that could be applied to HAOWT structures as well.
Knezevic et al. (2019)	Presented a DT framework concept for fatigue life estimation for operation and maintenance using FEA.	Damage prediction.	The proposed framework provided a faster and more accurate real-time structural response.	Modelling real-time conditions appeared to be specific to each case and cannot be generalised.

components as well as monitoring of loads using strain gauge measurements (Ziegler et al. 2017).

5. Application of digital twin to fatigue in HAOWT structures

Digital twin (DT) in this review, is considered as a real term operation of physical asset which involves three key components given as: (i) digital model of the physical asset; (ii) changing data set retrieval; and (iii) dynamic updating of the model (Wright and Davidson 2020). Theories underlying physical systems and obtained data are applied to build a model which replicates these physical systems producing accurate representations. Information acquired from sensors can be integrated within simulations to predict real-time performance, forecasting, and fault detection. Recent advancements and deployment of IoT enable fast transition of captured multiscale properties using sensors, which can also be beneficial for the application of DT. History data from physical components can be used in the prediction of future component failure in engineering systems. It has been predicted that 25 billion sensors should have been in use by 2021 (Gartner 2018), which emphasises the trend of using data-driven approaches to further optimise existing and new engineering systems. Many digital twin software tools are currently available or in a process of development from technology providers including Microsoft, GE, IBM, Siemens, Oracle etc. This indicates that more DT are expected to be widely applied to sectors of the economy, including engineering. For instance, it has been applied in the manufacturing sector for product optimisation, the automotive sector for vehicle performance, the retail sector for customer experience, the healthcare sector for patient monitoring, as well as in smart cities for planning, oil and gas and renewable energy for asset maintenance. Thus, simulation-based and data-driven DT can provide benefits in condition monitoring of physical assets and their maintenance.

Figure 7 shows that condition-based maintenance (diagnostics/preventive), predictive maintenance (prognostics), and prescriptive maintenance (optimised solutions) are key areas of DT applications in the energy sector (Errandonea et al. 2020). There has been a sudden rise in research on DT for maintenance since about 2017 in most of the sectors, as well as a sizable number of DT applications also recorded in the energy sector. DT application for fatigue assessment has also been applied in the aerospace industry (Leser et al. 2020), to oil and gas semisubmersible drilling rigs using reduced-basis finite element analysis and corrosion management (Sharma et al. 2018; Adey et al. 2020), to industrial machines (Zhidchenko et al. 2019) and general engineering systems (Ekoyuncu et al. 2019). Numerous DT frameworks have been proposed by researchers to focus on different maintenance applications. Physics-based predictive maintenance frameworks have been proposed based on modelling of physical phenomena (e.g. fatigue using sensor data and models) to predict remaining life (Georgoulias et al. 2019). Cloud-based DT applications could offer remote high-speed computing and efficient data storage resulting in potential cost-savings. DT material degradation frameworks, that can be applied to structural steel in offshore wind turbines for damage estimation and prediction of remaining life, could also adopt cloud-based ML capabilities (Ekoyuncu et al. 2019). Incorporation of DT frameworks for real-time diagnostics and long-term prognostics could aid efficient scheduling for inspections.

Table 4 summarises relevant work from literature, specific to the application of DT to corrosion and fatigue assessment in HAOWT aiming to identify published work, benefits of DT use and potential areas for further development.

DT concept in the wind energy industry has been considered as a means of capturing real time data from sensors and feeding it into FEA models (Sharma et al. 2018). DT frameworks have been proposed for general condition monitoring, but there is a lack of DT frameworks coupling condition monitoring for wind power generation and fatigue analyses. The DTs developed for wind power applications seem to be more predictive rather than prescriptive. Development of data-driven and simulation-based DTs, for existing and new HAOWTs, is an opportunity to reduce maintenance and repair costs. Cloud computing is another opportunity that can enhance the deployment of more DT in HAOWT applications. A recent example is Shell partnering with Kongsberg Digital to develop a digital twin for remote operation optimisation using cloud computing (Stump 2020). DT for fatigue monitoring in HAOWT could incorporate physics-based FEA, 5G and IoT technologies, sensors for data collection, data analytics and ML technologies (e.g. ANN). Based on the conducted literature review in this study, a digital twin framework is proposed in Figure 8 to provide a general overview. As an exemplar for the application of corrosion fatigue assessment, material characterisation testing can be performed to generate S-N curves which includes notch effects, stress concentrations and surface and pitting effects. This is then utilised in FEA analysis to generate data sets incorporating corrosion and fatigue effect. These data sets can be further used to train ANN models which can obtain real-life data from actual operating HAOWT where rainflow algorithms combined with damage calculations (e.g. Miner's rule) could be applied to predict the remaining life.

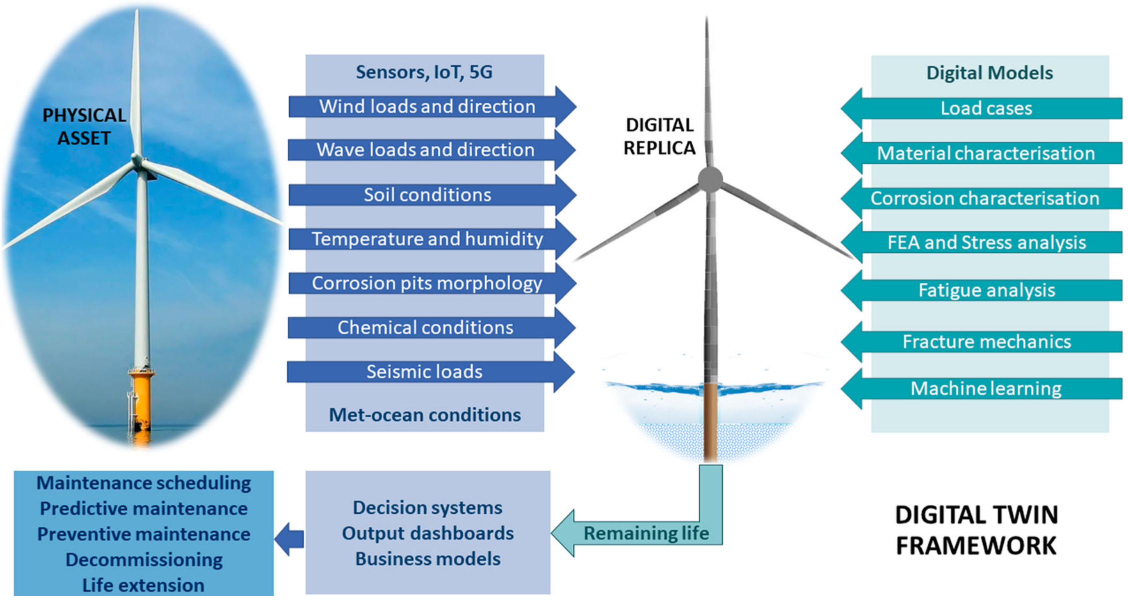


Figure 8. Digital twin framework for enabling corrosion fatigue assessment in monopile supported offshore wind turbine (This figure is available in colour online).

6. Conclusion and future perspectives

Current approaches in the use of digital tools for corrosion fatigue damage on HAOWT have been reviewed (e.g. finite element analysis, machine learning, digital twins). The following key challenges and future perspectives were derived from this study:

- The wind energy sector is still faced with challenges from aerodynamic and hydrodynamic actions, soil-structure interaction issues, and environmental factors in harsh operating conditions as large-diameter offshore wind turbines are now being installed in deeper waters for higher capacity power production. Thus, this new level of upscale in capacity and size brings about more corrosion fatigue challenges in HAOWT. The combination of cathodic protection and vibration mitigation techniques has been used to reduce corrosion rate and cyclic load respectively. Hence, improving the fatigue life is needed when implemented at early stages of manufacture, installation, and operation.
- Improved steel grades of structural steel have been developed and are currently applied in the manufacturing of wind turbines. To accurately quantify the effect of corrosion fatigue on the remaining life of these steels (i.e. pitting, crack initiation and crack propagation and growth effects), more experimental works is required. Availability of reliable experimental data would increase the accuracy of computational models and be able to predict the fatigue damage in corrosive environments with greater accuracy.
- Advancement in structural and material damage assessment simulation tools have shown enormous potential in detecting, analysing, and predicting fatigue damage. Further improvements for using representative S-N curves capturing notch effects to cater for weld damages, thickness effects to consider corrosion loss, and stress concentration factors are needed.
- Pitting, which is affected by material and environmental factors, can have detrimental effects on monopile components. Pits can become a source for crack initiation leading to reduced fatigue life. In the consideration of corrosion fatigue damage at weldments of offshore wind turbine support structures, fatigue S-N curves must factor the effects of pit size and morphology.
- There is insufficient knowledge on the pit-crack transition stage in corrosion fatigue for the fundamental understanding of the overall fatigue damage process, Thus, finite element analysis models could further help to understand the relationship between crack initiation and pitting by considering material behaviour, soil conditions and sea waves on HAOWT structures. In addition to this, more experimental works on corrosion fatigue is needed to address the pitting effects.
- Computational analyses that consider the dynamic impacts of seawater, wind, and soil structure on HAOWT support structures are encouraged as they can provide further understanding for the development of representative load cases for fatigue analyses. Particularly, the use of computational fluid dynamics for wave loading and modelling of different soil conditions can give insight into both cyclic responses and stiffness effects of soil located in various sites globally.
- Data obtained from real-time condition monitoring of offshore wind turbines (i.e. in-service loads) need to be considered in damage assessment models in a standard prognostic system to boost operation and maintenance in the wind sector, specifically for HAOWT monopile support structures.
- Artificial neural network techniques using back-propagation neural network with a time-based predictive algorithm has been the most applied algorithm to fatigue prediction in the monitoring of HAOWT components. Artificial neural networks can perform fast predictions of environmental conditions affecting HAOWT components. However, their accuracy is dependent on the data quality which is used for training.
- Fatigue simulations based on finite element analysis showed the potential to provide training data needed to build an artificial neural network algorithm and reduce computational costs in its training phase. More research on optimisation algorithms for remaining fatigue life prediction is encouraged by using finite element analysis predicted data into machine learning approaches such as artificial neural networks.
- Digital Twin technologies have been used in wind energy for condition-based maintenance, and predictive maintenance. In addition, physics-based predictive maintenance showed to be more effective for fatigue consideration with a capacity to

combine multiple damage models for diagnostics and prognostics purposes. However, the digital twin frameworks presented by researchers for offshore wind turbines are conceptual and they need to be further explored in collaboration with industry to achieve their exploitation.

- Digital twins incorporating finite element analysis, material characterisation and modelling, artificial neural networks, data analytics, and internet of things using smart sensor technologies can tackle the challenges in corrosion fatigue assessment of offshore wind turbines.

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No potential conflict of interest was reported by the author(s).

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